Spillway Discharge Measurements by Acoustic Scintillation Flow Meter in Spillway B at Mellanfallet Dam, Alvkarleby Hydro Power Station, Sweden, August, 1999

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Swedpower AB
SE-814 26 Alvkarleby
Alvkarlebylaboratoriet,
Sweden

By

W. W. Cartier, D. D. Lemon and R. A. Chave
ASL Environmental Sciences Inc.
Sidney, B.C. V8L 5Y3
Canada

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Summary

ASL Environmental Sciences Inc. was contracted by SwedPower AB, Alvkarleby Laboratory, Sweden to use a 9-path Acoustic Scintillation Flow Meter in the spillway at the Mellanfallet Dam, Alvkarleby Hydro Power Station, Sweden. The frame, supplied by SwedPower, was rigged with transducers and cabling and installed in the spillway during the 16th and 17th of August, 1999. These operations involved both ASL and SwedPower personnel. Discharge measurements were performed on spillway B, and ASL operated the ASFM to collect flow data during the tests. This report outlines the operational principles of the ASFM, then describes its installation in the plant and the collection of the data. Measurements were made for four different spillway openings:

1) 0.50m spillway opening.

2) 0.75m spillway opening.

3) 1.00m spillway opening.

4) Fully open spillway.

The data collected by the ASFM consisted of the magnitude and inclination of the laterally-averaged velocity at each of 9 elevations in the spillway.

Despite the installation of the semi-circular plates, vortices formed by a flow contraction around the H-beams caused air entrainment down past the upper pair of transducers at full gate opening, so that no acoustic signals were received on that level.

During the data collection it became apparent that the velocity computation algorithm was underestimating the flow velocities and hence the discharge, particularly at larger gate openings. A boundary layer separation from the leading edge of the fairing caused a re-circulation of flow within the boundary layer. This re-circulation region contained

more intense turbulence than the region outside of the boundary layer, resulting in low velocity estimates and hence low discharge estimates.

The ASFM technique shows promise for directly measuring spillway capacity, but the method of mounting the sensors must be improved so that vortex formation and the introduction of air in front of the sensor faces is prevented. Otherwise, as was seen at Mellanfallet Dam, it is not possible to measure the maximum discharge capacity, which is the quantity of interest

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1. Introduction

ASL Environmental Sciences Inc. was contracted by SwedPower AB, Alvkarleby Laboratory, Sweden to use a 9-path Acoustic Scintillation Flow Meter in the spillway at the Mellanfallet Dam, Alvkarleby Hydro Power Station, Sweden. The frame, supplied by SwedPower, was rigged with transducers and cabling and installed in the spillway during the 16th and 17th of August, 1999. This operation involved both ASL and SwedPower personnel. Discharge measurements were performed on spillway B during the 18th and 19th of August, 1999, and ASL operated the ASFM to collect flow data during the tests.

The ASFM uses a technique called acoustic scintillation drift to measure the flow speed of water perpendicular to a number of acoustic paths established across the spillway entrance. Fluctuations in the acoustic signals transmitted along the paths result from turbulence in the water carried along by the current. The ASFM measures those fluctuations (known as scintillations) and from them computes the lateral average (i.e. along the acoustic path) of the flow perpendicular to each path. Both the magnitude and inclination of the flow speed are measured. The ASFM computes the discharge through the spillway entrance by integrating the horizontal component of the flow speed over its height. Acoustic scintillation drift is a non-intrusive method; no instruments are required in the measurement zone, minimizing interference with the flow, or damage to measurement equipment from debris passing through the spillway opening. Measuring the lateral average of the component of the flow perpendicular to the acoustic path allows the ASFM to operate without being affected by large-scale eddies or meandering; it is therefore well-suited for use in spillways and other low-head, short intake dams whose geometry makes the application of other methods difficult.

Scintillation drift was first applied to the measurement of winds in the ionosphere and atmosphere, using light or radio waves. The first applications to water flow using acoustic scintillation signals were for measuring currents and turbulence in ocean channels and rivers (Clifford & Farmer, 1983; Farmer & Clifford, 1986; Clifford, Farmer & Verrall, 1987; Lemon & Farmer, 1987).

In 1992, the first acoustic scintillation measurements done in the hydroelectric industry were done to measure turbine discharge at Rocky Reach Dam. A set of calibration measurements were made in a tow tank to establish the accuracy of the velocity measurement in 1994 (Lemon, 1995). Favourable results obtained there led to comparison measurements against current meters for discharge at two different plants in 1997 (Lemon, Caron, Cartier & Proulx, 1998; Lemon et al, 1998).

Scintillation drift requires only a relative measure of the acoustic signal strength at the receiver; the time lag between the two time series of the signal fluctuations is used to compute the spatially averaged flow speed. There is therefore no necessity to calibrate the transducers in the system. As long as they are sufficiently close in response that the signal is within the range of the digitizer, there is no need for periodic calibration.

The ASFM's ability to measure the absolute discharge in geometry typical of spillways was the reason for its use in the spillway B at Mellanfallet Dam. Measurements were made for four different spillway openings:

1) 0.50m spillway opening.

2) 0.75m spillway opening.

3) 1.00m spillway opening.

4) Fully open spillway.

The data collected by the ASFM consisted of the magnitude and inclination of the laterally-averaged velocity at each of 9 elevations in the spillway. The discharge through the spillway for each condition were then computed from the velocity measurements. The results are presented as tables and plots of the velocity and the discharge.

This report presents the final values for the flow speeds and discharges measured by the ASFM, after verification and checking.

2. Installation at Mellanfallet Dam

2.1 ASFM Installation

The ASFM was scheduled for installation in spillway B at Mellanfallet Dam and was to be configured with nine acoustic paths.

Figure 2-1 shows a schematic diagram of the components of the ASFM as installed in the spillway. The transducers and switching canisters were installed on the spillway deck. Figure 2-2 shows the location of the measurement plane in the spillway and its relationship to the spillway entrance when installed. The transducer support frames were designed and supplied by SwedPower.

The work was scheduled to be completed over two phases. The first phase; to install the frame and test it for vibration and general performance, the second phase; to perform flow measurements for four different gate openings, one with the gate open to 0.5m, one with the gate open to 0.75m, one with the gate open to 1.0m and one with the gate fully open. ASFM flow measurements were done during the second phase and occurred during the 18^{th} and 19^{th} of August, 1999.

Vibration testing indicated that the frames did not have any serious vibrations through the full operating range of the spillway. Figure 2-3 shows the transducer support frame being installed for the vibrations tests without the ASFM equipment mounted. Figure 2-4 shows a detail of the vibration sensor mounted on the top of the support frame. Figure 2-5 and Figure 2-6 show flow through spillway opening during vibration testing and entrainment of air around the vertical section of the frame during vibration testing respectively. Fairings formed from semi-circular plates mounted between the upstream part of the H-beams and the dam walls were designed to be mounted to the vertical sections of the support frames to try to minimize the effects of air entrainment in front of the transducers.

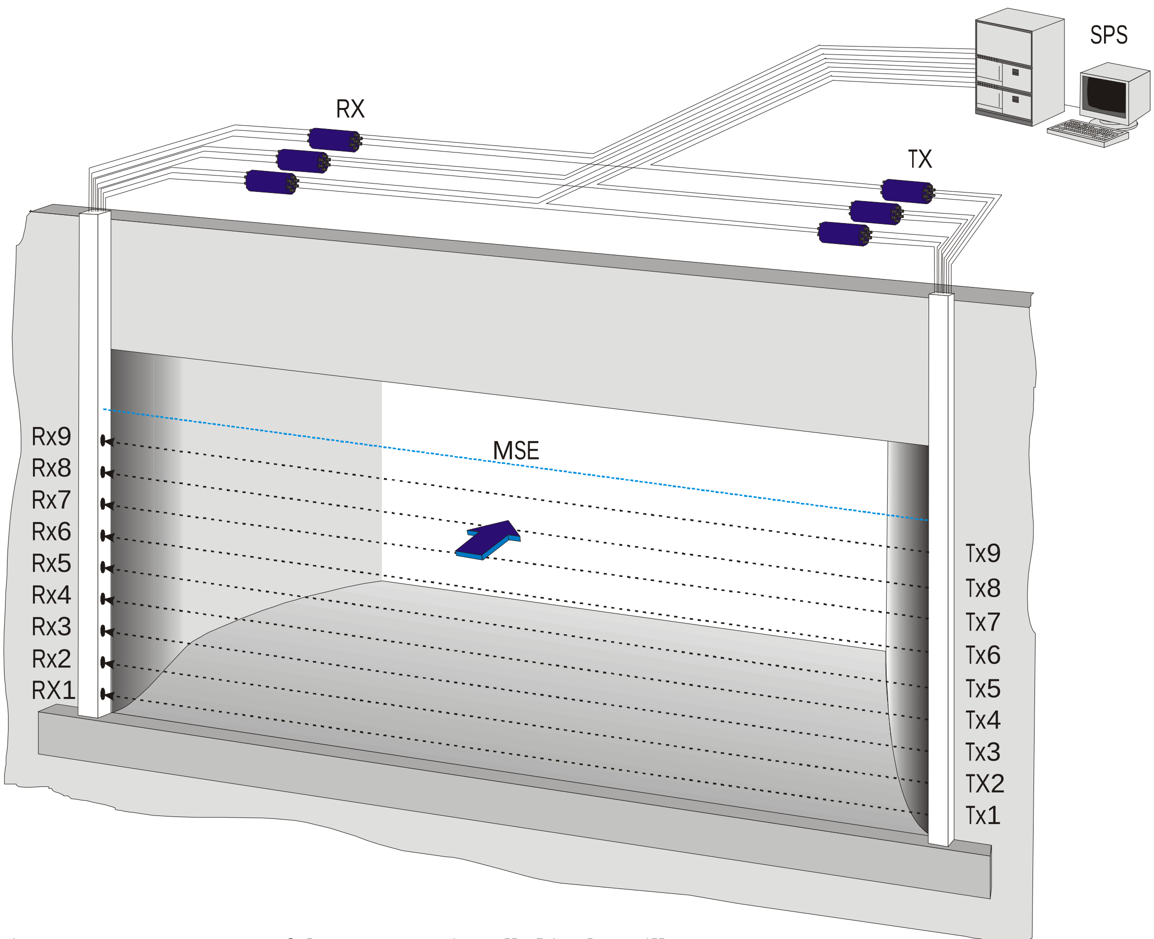

Figure 2-1: Components of the ASFM as installed in the spillway.

The frames were on site in a laboratory building when ASL personnel arrived at Mellanfallet Dam on August 16th. The frames were stored horizontally on pallets, set up on the floor, to facilitate the installation of the ASFM components. Figure 2-7 shows the frames after the ASFM components had been installed prior to installation in the spillway, and a detail of the transducer mounting and cabling. One of the frames is shown with the cover plate installed and the other with the transducers and cabling exposed. By the end of August 16th the ASFM components were fully mounted on the support frame and measurements of the relevant geometric parameters were done on the frame.

By the end of Wednesday August 17th, the support frames had been installed in spillway B, along with the fairings which were mounted after the support frame had been attached to the face of the spillway (Figure 2-8). Figure 2-11 shows the resulting flow around the fairings, which unfortunately did not completely solve the air entrainment problem. Gate openings greater than 1m resulted in unusable upper levels. Figure 2-9 shows the spillway in operation with the spillway gate fully open.

On the morning of August 18th the surface control module was set up in a trailer (supplied for the purpose by SwedPower) parked on the deck of spillway B (Figure 2-10). Details of the required installation and operating procedures for the ASFM may be found in ASL Environmental Sciences Inc. (1997).

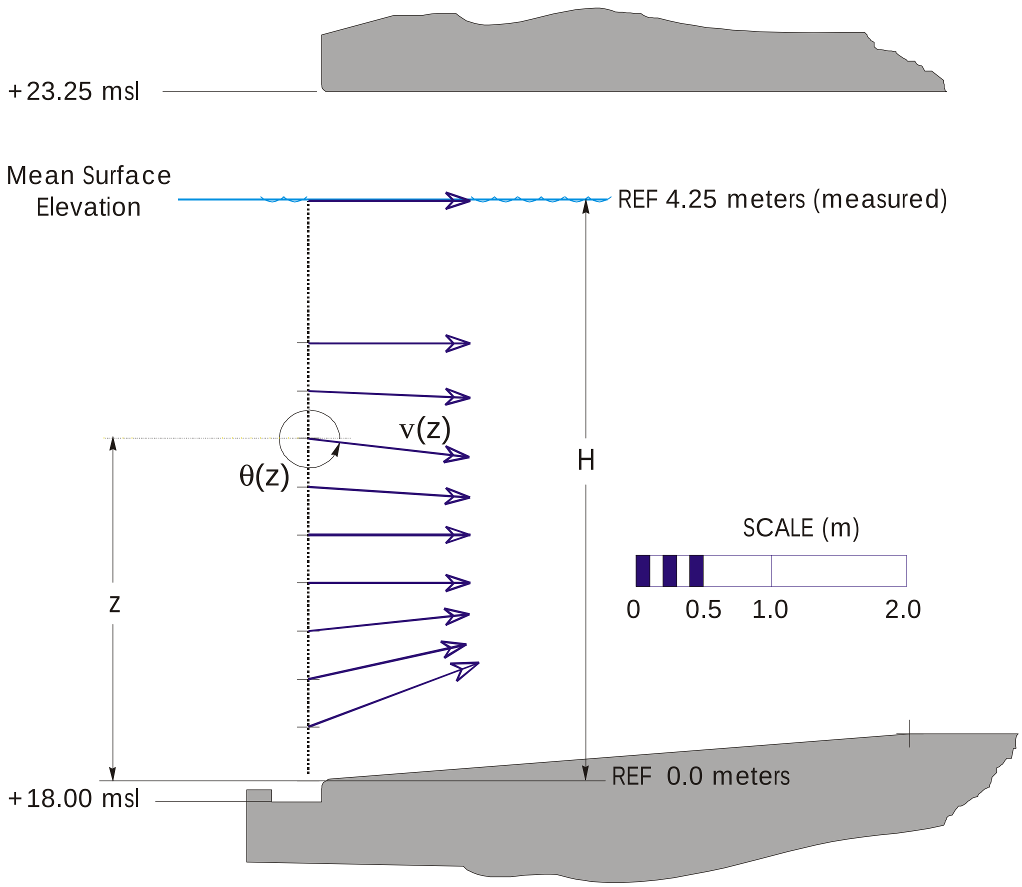

Figure 2-2: Location of the measurement plane in the spillway, and definition of associated parameters.

The support frame is shown schematically in Figure 2-12. The bottom cross-member was designed to sit in a small trough at the foot of the spillway opening (Figure 2-2) and sit flush with the floor of the spillway opening. This coupled with the flush mounting of transducers and no other bracing or mounting structures in the spillway was expected to cause very little flow interference. The transducers were placed at the upstream edge of the side faces to minimize acoustical multipath interference with the sides of the spillway opening. The transducers and cabling were protected from any debris carried along with the flow.

The measurement plane was roughly 0.15 m in front of the spillway opening and the measurement was made with nine acoustic levels. The base of the measurement frame was at the elevation +18.15 m.s.l., the vertical sides of the frame were formed by H-beams fastened to the needle guidance rails used for temporary closure. The distance between the vertical beams was 11.0 m.

Transducers were mounted on the H-beam with the transmitters on one side and the receivers on the other as shown schematically in Figure 2-1. The open side of the H-beam was covered with a protective aluminium plate with holes for the transducers as shown in Figure 2-7. Nine acoustic levels (transducers RX1 through RX9 and TX1 through TX9), in the entrance to the spillway, were mounted on the two vertical H-beams. These eighteen transducers were cabled to the surface to six pressure cases (RX and TX), which in turn were cabled to the surface data acquisition and control system (SPS). Levels one, two and three were cabled to the first set of pressure cases (RX and TX), levels four five and six were cabled to the second set of pressure cases and levels seven, eight and nine were cabled to the third set. MSL indicates the expected mean water surface elevation. Figure 2-9 shows a photograph of the spillway in operation with the ASFM system installed.

Figure 2-12 defines the five geometrical parameters, which had to be measured before the frame was deployed. They were measured with the frame lying on the floor. The angles j_T and j_R are the deviation of the transducer reference plane from the horizontal (when the frame is vertical on the face of the spillway), L is the intake width at each transducer level (i.e. the measured distance between the faces of the transmitting and receiving transducers at that level), and Z_T and Z_R are the elevations of the transducers on each side of the frame, measured from the floor of the spillway. All the parameters were measured

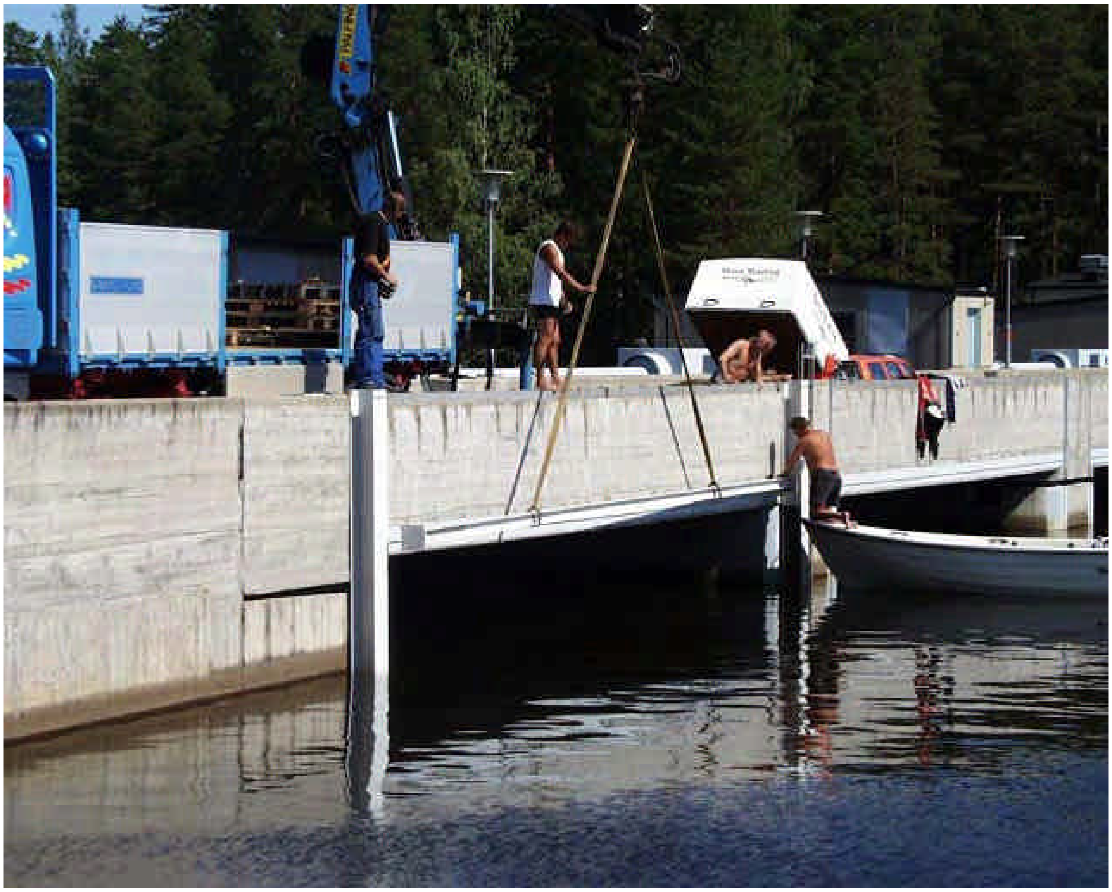

Figure 2-3: Transducer support frame being installed prior to vibration testing.

before the frame was installed in the spillway. The elevation of each level was defined as

$$Z = (Z_T + Z_R)/2,$$

and the correction to the horizontal reference as

$$j = (j_T + j_R)/2.$$

Table 2-1 lists the values of the dimensional parameters including the elevations Z, path lengths L and angular corrections j.

Figure 2-4: Detail of vibration testing equipment.

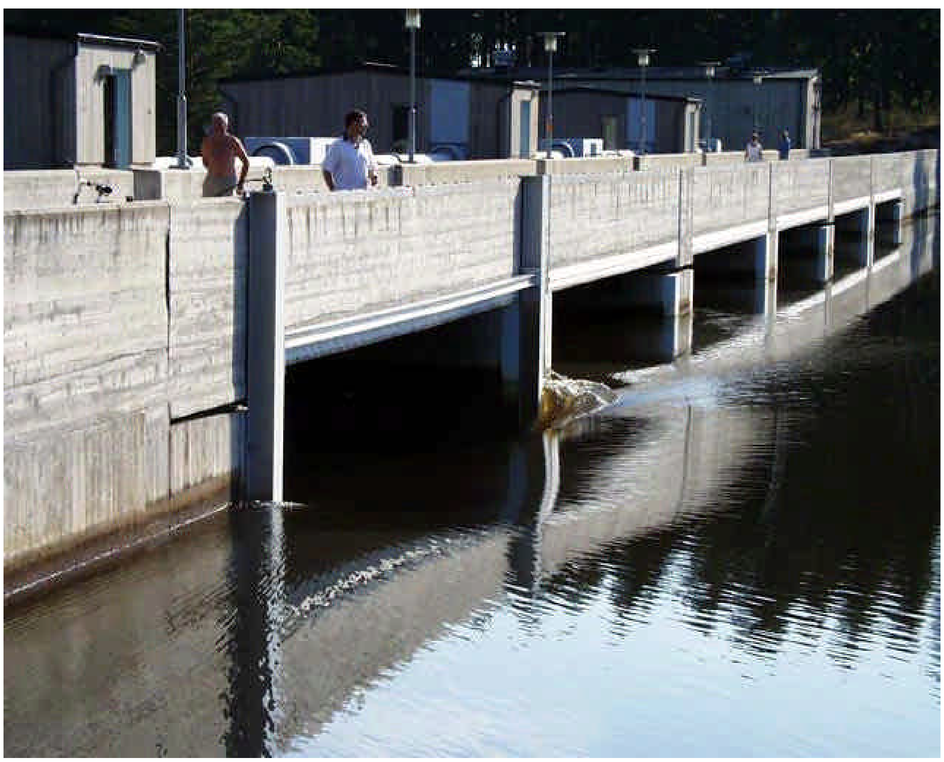

Figure 2-5: Flow through spillway opening during vibration testing (no fairings present).

Figure 2-6: Entrainment of air around frame during vibration testing (indicated by white arrow).

Figure 2-7: ASFM transducer support frame rigged prior to installation in spillway.

Figure 2-8: Transducer support frame fairings being installed prior to flow measurements.

Figure 2-9: Spillway B in operation during flow tests..

Figure 2-10: Trailer used to house the ASFM surface processing system.

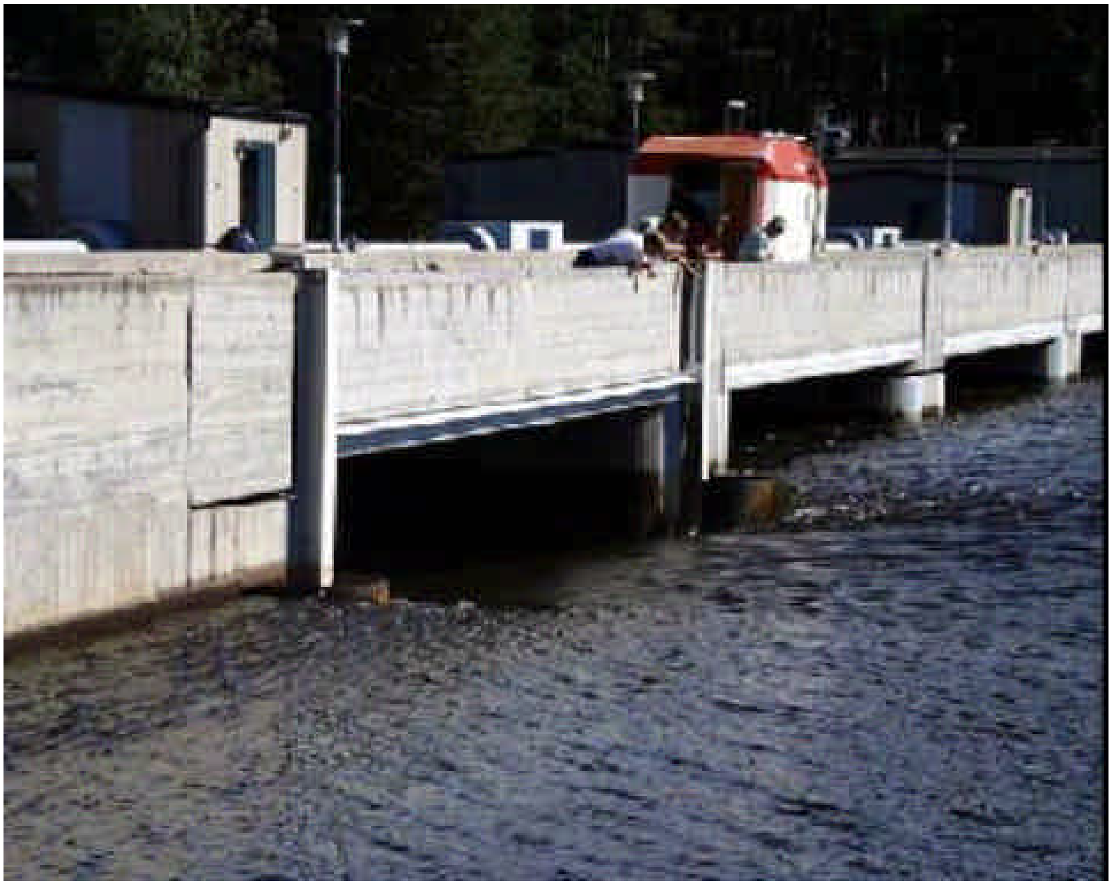

Figure 2-11: Flow around fairings during flow measurements.

The frame used during these tests was the first frame ever designed to support an ASFM for a spillway application. Its design and construction made installation of the ASFM components simple. Although the construction of the frame was exemplary, and it presented no vibration problems, there were two major problems resulted from its design. Vortices formed in front of the frame caused entrainment of air in front of the upper transducers during gate openings greater than 1m. This precluded any tests of the spillway during full gate opening.

Second, a turbulent boundary layer was set up in front of the transducers, resulting in a non-uniform distribution of turbulence intensity along the acoustic paths joining the transmitters to the receivers. These combined problems resulted in poor results from the ASFM system for all but the 0.5 m gate opening.

Table 2-1: Dimensional Data, Mellanfallet Dam.

	Path	Level Assignment	Color Designation	Path Length (m)	Angle Deviation (deg)	Average Elevation (m)
Top of Frame	A09	GA03-03	Red	11.01	0.0	3.190
	A08	GA02-03	"	11.01	0.0	2.835
	A07	GA01-03	"	11.01	0.0	2.480
	A06	GA03-02	Brown	11.01	0.0	2.125
	A05	GA02-02	"	11.01	0.0	1.770
	A04	GA01-02	"	11.01	0.0	1.415
	A03	GA03-01	orange	11.01	0.0	1.060
	A02	GA02-01	"	11.01	0.0	0.705
Bottom of Frame	A01	GA01-01	"	11.01	0.0	0.350

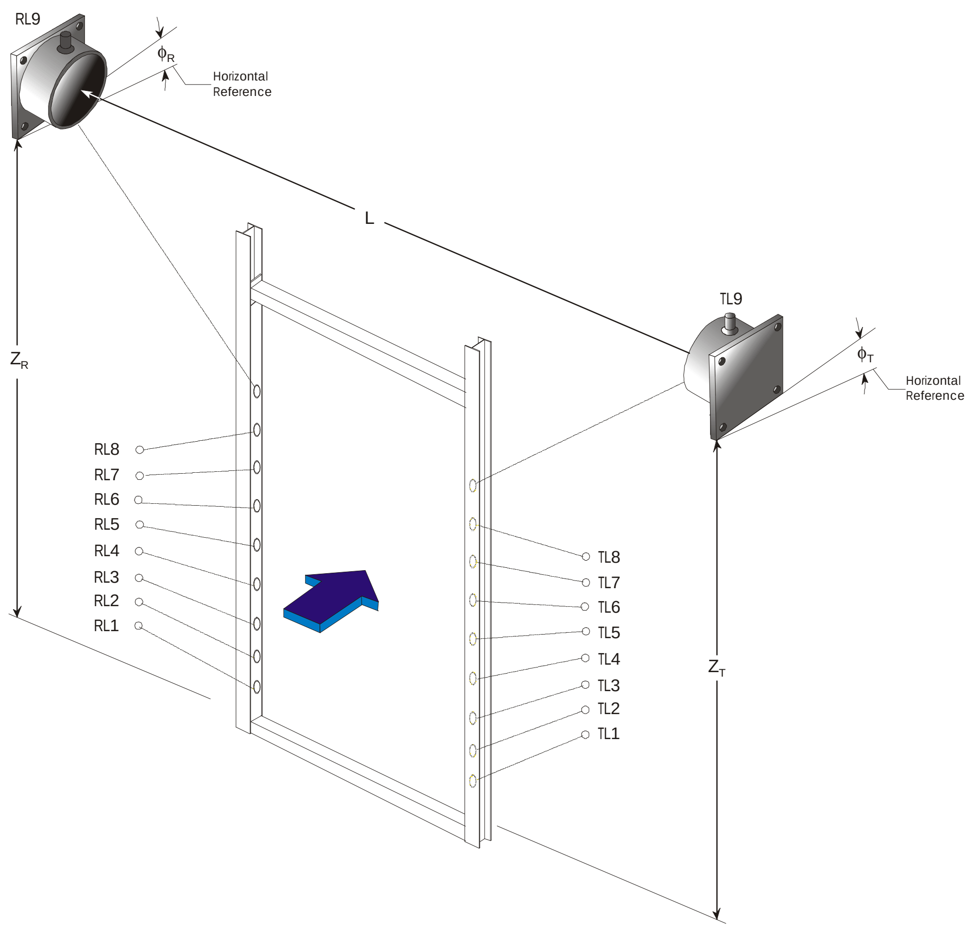

Figure 2-12: Path layout on the frame and definition of geometrical parameters.

2.2. Operational Checks

Once the ASFM frame had been installed, the surface cables were connected to the data acquisition and control module in the instrument trailer the morning of August 18th, 1999. Initial operational checks were performed and the ASFM system was operational after a small correction to an intermittent cable connection in the data acquisition and control module was made.

The ASFM uses time-division multiplexing to separate and identify the signals arriving at the receiver. The transmitters do not send sound signals continuously, but are pulsed in a set pattern. Reflected signals arriving over a route other than the direct path between the transmitter and receiver can interfere with the expected pulse pattern at the receiver and confuse the signal identification process. Theses reflections, called multipaths, can arise because the transducers have a beam 10° wide, and weaker side-lobes as well. Normally, interference arises when signal paths are too close to surfaces, so that multipaths overlap the direct signal. The path lengths entered to the program were used by the ASFM to compute the precise arrival time for each transmission, and therefore eliminated the confusion caused by the extraneous echoes. The measured water temperature, 18.3°C, was entered as an input yielding a sound speed of roughly 1478m/s which improved the precision of the arrival time calculation. Fortunately no interfering reflections were present and the ASFM system functioned normally and successful acoustic signal acquisition was confirmed for all paths with no flow through the spillway. No-flow conditions produce nearly constant signal amplitude levels, as the absence of flow means there is no turbulence present to produce scintillations. Since the scintillations are required by the ASFM to compute flow, no flow speeds can be computed without them. The absence of fluctuations under these circumstances confirms proper operation of the instrument and serves as a zero flow check.

In previous ASFM installations (e.g. at Lower Granite Dam in 1995; see Lemon, Chave & Clarke, 1995) vibration in the transducer support frame had been a source of some trouble. The frames used at Mellanfallet Dam had been previously tested for vibration and were shown to contain little or no troublesome vibrational modes. The spillway gate was opened to the full open position and data were collected to check for system operation. It was found that even with the installed fairings there was significant draw-down of the surface and entrainment of air in front of the upper level transducers rendering the top four levels unusable. Subsequent tests revealed that gate openings greater than 1m presented these draw-down and entrainment problems. No evidence of vibration effects (see ASL Environmental Sciences, 1997) were found.

During initial tests it was noted that a problem existed with flow direction and a wiring problem in one of the switching canisters was discovered. It was decided that reconfiguring the system to a single bay, three path, three frame position system and manually switching the transducers to the various levels, was the quickest way to resolve the problem. This was carried out successfully.

3. Data Collection

One set of measurements were made on spillway B at the Mellanfallet Dam and were taken for four different spillway openings:

1) 0.50m spillway opening.
2) 0.75m spillway opening.
3) 1.00m spillway opening.
4) Fully open spillway.

Data collection for conventional parallel paths began on 18 August 1999, at 18:41, and ended the same day at 21:50. Additional data was taken on 19 August 1999 to test an alternate transmission scheme, using converging acoustic paths, with which it was hoped would over-come the effects of the observed flow separation in front of both the transmitting and receiving transducers. Table 3-1 summarizes the data collection sequence.

Surface elevations across the gate opening as well as the surface velocity were measured by the Vattenfall personnel and are summarized in Table 4-1, Table 4-2 and Table 4-3 and plotted in Figure 4-1. These quantities were used to define the upper boundary levels.

Table 3-1: Schedule of Data Collection

Test	Configuration	Test Number	Date	Start (Local Time)	End (Local Time)
0.5m gate opening	Parallel Path	19	18-Aug-99	18:41	18:56
0.5m gate opening	Parallel Path	20	18-Aug-99	19:05	19:19
1.0m gate opening	Parallel Path	21	18-Aug-99	19:44	20:01
1.0m gate opening	Parallel Path	22	18-Aug-99	20:29	20:49
0.75m gate opening	Parallel Path	23	18-Aug-99	21:11	21:50
1.0m gate opening	Converging Path	24	19-Aug-99	14:53	15:20
Full gate opening	Converging Path	25	19-Aug-99	15:24	15:52
0.5m gate opening	Converging Path	26	19-Aug-99	15:55	16:20

After the final measurements were completed on 19 August 1999, the ASFM was shut down and demobilization was begun. The transducer support frames were removed and returned to the laboratory building on 20 August 1999 where they were stripped of the cabling and transducers. All ASFM equipment was crated and packed and prepared for shipment back to Canada.

4. Data Analysis and Results

Where possible, preliminary values for the velocity and discharge were produced immediately after each gate opening run. These were computed using the dimensions measured before deployment. During the data collection it became apparent that the velocity computation algorithm was underestimating the flow velocities and hence the discharge, particularly at larger gate openings.

Despite the installation of the semi-circular plates, the vortices formed by the flow contraction around the H-beams caused air entrainment down past the upper pair of transducers at full gate opening, so that no acoustic signals were received on that level.

A spectral analysis and careful filtering of the field data was performed during post processing. These results are shown in Table 4-4 and Table 4-5, the upper panel in table Table 4-4 shows the original field results and the lower panel shows the post processed data for the parallel path data.

Horizontal velocity plots for parallel path and converging path data are shown in Figure 4-18 and Figure 4-19 respectively. Horizontal velocity profile results for the 0.5m gate opening are shown in Figure 4-20.

4.1. Velocities

The laterally-averaged values of the flow speed and inclination along with vector plots for each path are shown in Figure 4-2 through Figure 4-17. Each page shows the flow condition data for each spillway gate opening. The start time for each level, its elevation, path length, speed, inclination angle and quality index are shown. The sample length was 90 seconds, except where otherwise noted. The same data are shown graphically on cross-sections of the spillway below the tabulated data for each gate opening. The base of each vector is located at the position in the spillway where the measurement was made. The length of the vector gives the magnitude of the flow, scaled by the legend in the diagram, and its direction shows the inclination. The number at the base of each vector is its magnitude in metres per second. The notations at the left of the figure detail the conditions under which the data were collected.

4.2. Discharge Computation

The free surface and floor of the spillway, and the path followed by the sides of the frame holding the ASFM transducers define a plane surface, *S*, through which the flow into the intake bay must pass. The discharge is therefore given by the flux through *S*:

$$Q = \oint_S \boldsymbol{V} \cdot \boldsymbol{n} \, da \qquad (1)$$

where ***V*** is the velocity vector (a function of position in the plane) and **n** is the unit vector normal to the plane. The ASFM measures the lateral average of the component of velocity normal to the propagation path; if *z* is the vertical coordinate, then the discharge, *Q*, in terms of the laterally-averaged velocity ***v*** is:

$$Q = \int_0^H v(z) \cos[\theta(z)] L \, dz \qquad (2)$$

where v(z) is the magnitude of the laterally averaged flow at elevation z, θ(z) is the corresponding inclination angle, *L* is the width between the transducer faces and *H* is the height of the free surface elevation relative to the floor. The lateral averaging performed by the ASFM is continuous, while the sampling in the vertical was at nine discrete points. Calculating *Q* then requires estimation of the integral in equation 2 when the integrand is known at a finite number of points. The integral was evaluated numerically using an adaptive Romberg integration, with a cubic spline interpolation in the integrand between the measured points. The measured points do not extend all the way to the free surface and floor; as a result, complete evaluation of the integral requires an evaluation of the flow in the zones next to those boundaries. The methods used are detailed in the following subsections.

4.2.1. Treatment of the Boundary Layers

Between the measured points at the upper and lower extremes and the corresponding boundaries at the free surface and floor, it was necessary to impose a form on the horizontal component of the velocity to allow the evaluation of integral to be completed. Different conditions apply at the free surface and the floor. Each of these cases will be described separately.

4.2.1.1. Floor

The boundary layer at the floor was estimated to be 0.1m thick.. The horizontal velocities of the lowest two levels were extrapolated, along a straight line, down to the boundary layer and then the velocity decreased to zero, along a curve of the form

$$[z/z_0]^{1/n}\ , \qquad (3)$$

between the floor and $z_0 = 0.1$ m elevation. The curve shape was set for n = 7 and the floor was treated as a simple combination of a standard boundary layer above the floor and an extrapolation from the lowest measured point to the top of the boundary layer.

4.2.1.2. Free Surface

The treatment at the open upper boundary depends on a cross-sectional measurement of the surface, which enables the determination of a mean elevation. Vattenfall personnel took this data and supplied it for this report in tabular form as shown in Table 4-1 through Table ***4-3***. The velocity of the surface was measured with a small portable mechanical current metre at several points along the surface and then averaged. This resulting horizontal velocity was set at the measured mean elevation. This point, defined the horizontal velocity at the free surface. Table 4-1 through Table 4-3 show the surface measurement data for the 0.5m, 1.0m and fully open gates respectively (the surface elevation data was not available for the 0.75m gate opening). Figure 4-1 shows the plots of these data in relation to the four upper most ASFM measurement levels, level six, level seven, level eight and level nine.

The draw down effects can clearly be seen in Figure 4-1 for the fully open gate on the extreme right side of the spillway down below the top most transducer of the ASFM. This does not show the severity of the air entrainment, which extended down past the several of the upper levels of the ASFM system rendering the data unusable.

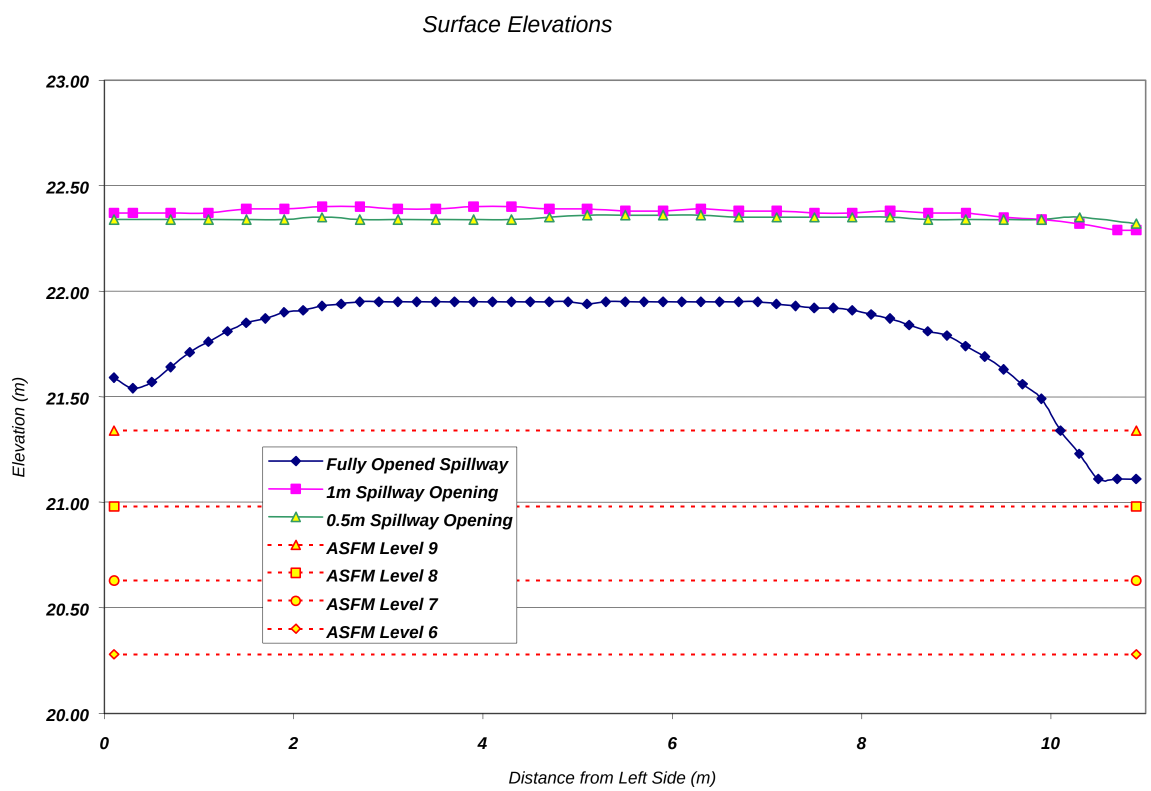

Figure 4-1: Surface profiles for 0.5m, 1.0m and fully open gate positions.

Table 4-1: Surface Measurements at 0.5m spillway opening.

		Water surface profile	
Our test number:		7	8
Spillway opening		0.5m	0,5m
Date:		990819	990819
Time:		16:05	16:15
Upstream water level:		+22.38	+22.40
Distance from left side			
Nr.	*[m]*	*[m]*	*[m]*
1	0.1	22.34	22.36
4	0.7	22.34	22.36
6	1.1	22.34	22.36
8	1.5	22.34	22.36
10	1.9	22.34	22.36
12	2.3	22.35	22.37
14	2.7	22.34	22.36
16	3.1	22.34	22.36
18	3.5	22.34	22.36
20	3.9	22.34	22.36
22	4.3	22.34	22.36
24	4.7	22.35	22.37
26	5.1	22.36	22.38
28	5.5	22.36	22.38
30	5.9	22.36	22.38
32	6.3	22.36	22.38
34	6.7	22.35	22.37
36	7.1	22.35	22.37
38	7.5	22.35	22.37
40	7.9	22.35	22.37
42	8.3	22.35	22.37
44	8.7	22.34	22.36
46	9.1	22.34	22.36
48	9.5	22.34	22.36
50	9.9	22.34	22.36
52	10.3	22.35	22.37
55	10.9	22.32	22.34

Table 4-2: Surface Measurements at 1.0m spillway opening.

		Water surface profile	
Our test number:		3	4
Spillway opening		1m	1m
Date:		990819	990819
Time:		14:35	15:05
Upstream water level:		+22,44	+22,42
Distance from left side			
Nr.	*[m]*	*[m]*	*[m]*
1	0.1	22.37	22.35
2	0.3	22.37	22.35
4	0.7	22.37	22.35
6	1.1	22.37	22.35
8	1.5	22.39	22.37
10	1.9	22.39	22.37
12	2.3	22.40	22.38
14	2.7	22.40	22.38
16	3.1	22.39	22.37
18	3.5	22.39	22.37
20	3.9	22.40	22.38
22	4.3	22.40	22.38
24	4.7	22.39	22.37
26	5.1	22.39	22.37
28	5.5	22.38	22.36
30	5.9	22.38	22.36
32	6.3	22.39	22.37
34	6.7	22.38	22.36
36	7.1	22.38	22.36
38	7.5	22.37	22.35
40	7.9	22.37	22.35
42	8.3	22.38	22.36
44	8.7	22.37	22.35
46	9.1	22.37	22.35
48	9.5	22.35	22.33
50	9.9	22.34	22.32
52	10.3	22.32	22.30
54	10.7	22.29	22.27
55	10.9	22.29	22.27

Table 4-3: Surface Measurements at fully opened spillway.

Data from our measurement of the water surface profile and water surface velocity during the test.
We measured the water profile 180 and 60 mm in front of the dam wall.
We have recalculated the water profile to the same distance as the transducer centre, 149 mm in front of the dam wall.
Distance between transducers: 11010 mm
according to your measurement when we mounted the frame in our labhall.
The distance are relative the transducer windows at the left side if you look at the frame from the upstream side.

		Water surface profile		Water surface speed
Our test number:		5	6	1
Spillway opening		Fully	Fully	Fully
Date:		990819	990819	990818
Time:		15:30	15:45	10:50
Upstream water level:		+22.41	+22.40	+22.45
	Distance from left side			
Nr.	*[m]*	*[m]*	*[m]*	*[m/s]*
1	0.1	21.59	21.58	
2	0.3	21.54	21.53	
3	0.5	21.57	21.56	
4	0.7	21.64	21.63	2.86
5	0.9	21.71	21.70	
6	1.1	21.76	21.75	2.68
7	1.3	21.81	21.80	
8	1.5	21.85	21.84	2.88
9	1.7	21.87	21.86	
10	1.9	21.90	21.89	2.73
11	2.1	21.91	21.90	
12	2.3	21.93	21.92	2.83
13	2.5	21.94	21.93	
14	2.7	21.95	21.94	2.68
15	2.9	21.95	21.94	
16	3.1	21.95	21.94	2.73
17	3.3	21.95	21.94	
18	3.5	21.95	21.94	2.81
19	3.7	21.95	21.94	
20	3.9	21.95	21.94	2.78
21	4.1	21.95	21.94	
22	4.3	21.95	21.94	2.78
23	4.5	21.95	21.94	
24	4.7	21.95	21.94	2.78
25	4.9	21.95	21.94	
26	5.1	21.94	21.93	2.78
27	5.3	21.95	21.94	
28	5.5	21.95	21.94	2.81
29	5.7	21.95	21.94	
30	5.9	21.95	21.94	2.81
31	6.1	21.95	21.94	
32	6.3	21.95	21.94	2.86
33	6.5	21.95	21.94	
34	6.7	21.95	21.94	2.86
35	6.9	21.95	21.94	
36	7.1	21.94	21.93	2.88
37	7.3	21.93	21.92	
38	7.5	21.92	21.91	2.93
39	7.7	21.92	21.91	
40	7.9	21.91	21.90	3.01
41	8.1	21.89	21.88	
42	8.3	21.87	21.86	3.06
43	8.5	21.84	21.83	
44	8.7	21.81	21.80	3.13
45	8.9	21.79	21.78	
46	9.1	21.74	21.73	3.18
47	9.3	21.69	21.68	
48	9.5	21.63	21.62	3.23
49	9.7	21.56	21.55	
50	9.9	21.49	21.48	3.18
51	10.1	21.34	21.33	
52	10.3	21.23	21.22	
53	10.5	21.11	21.10	
54	10.7	21.11	21.10	

4.3. Spillway Discharge Results

Despite the installation of the semi-circular plates, as shown in Figure 2-8 and Figure 2-11, the vortices formed by the flow contraction around the H-beams caused air entrainment down past the upper pair of transducers at full gate opening, so that no acoustic signals were received on that level.

Intermittent effects of the air entrainment were apparent at the next three levels below, causing severe signal interference, so that insufficient data could be obtained to make a meaningful discharge computation. Only at the lowest gate opening (0.5 m) were the entrainment effects small enough so that usable data could be obtained; in that case discharges of 18.4 m^3/sec and 23.6 m^3/sec were measured.

All data taken in the field in addition to reprocessed data has been presented in summary in Table 4-4 and Table 4-5. In addition, all of the field discharge data has been presented, as well as vector plots of the associated data, in Figure 4-2 through Figure 4-17.

Horizontal velocities show a large amount of variability as shown in Figure 4-18 and all but the 0.5m gate opening seem to under-estimate the spillway discharge. Even the 0.5m gate horizontal data, as shown isolated in Figure 4-20 shows a large amount of variability and the two repeat runs at this gate opening show a 28.3% difference in the discharge estimate. Typically in hydro turbine intake studies repeat discharge estimates with the ASFM differ by less than 0.5%.

It is believed that the addition of the metal fairings, which were put in place to help alleviate the extreme draw-down adjacent to the upper level transducers, caused a boundary separation upstream of the transducers. Figure 4-21 shows a pictorial of this process which resulted in a re-circulation region between the boundary layer separation point and the transducer face (on both sides of the spillway) resulting in a non-uniform distribution of turbulence intensity along the acoustic path joining the transmitters and receivers at all levels. It is fundamentally important to have a uniform distribution of small-scale turbulence intensity along the acoustic path or the regions of flow

Table 4-4: Summary discharge results for conventional parallel acoustic path data.

Horizontal Velocities (m/s)

Parallel Paths							
Elevation (m)	Test19 (0.5m Gate Opening)	Test20 (0.5m Gate Opening)	Elevation (m)	Test21 (1.0m Gate Opening)	Test22 (1.0m Gate Opening)	Elevation (m)	Test23 (0.75m)
4.24	0.54	0.54	4.24	1.04	1.04	4.25	0.76
3.19	0.5196	0.3998	3.19	0.7125	0.8650	3.19	0.6128
2.835	0.5047	0.4803	2.835	0.7415	0.7302	2.835	0.6154
2.48	0.4886	0.5457	2.48	0.6719	0.6026	2.48	0.5163
2.125	0.4507	0.4120	2.125	0.7134	0.7082	2.125	0.5594
1.77	0.5152	0.4849	1.77	0.7628	0.8045	1.77	0.6536
1.415	0.5014	0.4814	1.415	0.9614	0.9487	1.415	0.6906
1.06	0.4660	0.5513	1.06	0.9505	0.9609	1.06	0.8158
0.705	0.4528	0.4841	0.705	1.0160	0.9770	0.705	0.8908
0.35	0.5455	0.5351	0.35	1.1167	1.1319	0.35	0.9171
Discharge (m^3/s)	20.7030	19.3690		44.3400	45.6450		38.2570

Horizontal Velocities (m/s) - Reprocessed Data (Filtering)

Parallel Paths							
Elevation (m)	NewTest19 (0.5m Gate Opening)	NewTest20 (0.5m Gate Opening)	Elevation (m)	NewTest21 (1.0m Gate Opening)	NewTest22 (1.0m Gate Opening)	Elevation (m)	NewTest23 (0.75m)
4.24	0.54	0.54	4.25	1.04	1.04	4.25	0.76
3.19	0.5205	0.3978	3.19	0.7365	0.8799	3.19	0.6424
2.835	0.5047	0.4803	2.835	0.7824	0.7988	2.835	0.6346
2.48	0.4886	0.5432	2.48	0.6635	0.5818	2.48	0.4966
2.125	0.4630	0.4089	2.125	0.7342	0.7252	2.125	0.5600
1.77	0.5152	0.4870	1.77	0.7721	0.7975	1.77	0.6555
1.415	0.5076	0.4825	1.415	0.8974	0.9152	1.415	0.7066
1.06	0.4857	0.4837	1.06	0.9038	0.9338	1.06	0.7619
0.705	0.4705	0.5095	0.705	1.0023	0.9474	0.705	0.8107
0.35	0.5485	0.5361	0.35	1.0482	1.0764	0.35	0.8287
Discharge (m^3/s)	23.5830	18.3890		47.7930	52.5860		39.6340

Table 4-5: Summary discharge results for converging acoustic path data.

Horizontal Velocities (m/s)

Converging Paths					
Elevation (m)	Test 24 (1.0m Gate Opening)	Elevation (m)	Test25 (Full Gate Opening)	Elevation (m)	Test26 (0.5m Gate Opening)
4.24	1.0400	4.24	2.8900	4.24	0.5400
3.19	1.6295	3.19	15.4870	3.19	0.5770
2.835	0.5873	2.835	0.7315	2.835	0.3544
2.48	0.9678	2.48	2.0995	2.48	0.4615
2.125	0.6463	2.125	1.0327	2.125	0.5530
1.77	0.5343	1.77	1.2484	1.77	0.3817
1.415	0.9799	1.415	2.3881	1.415	0.6047
1.06	1.9842	1.06	0.4497	1.06	0.5750
0.705	0.7698	0.705	2.0037	0.705	0.5122
0.35	0.9839	0.35	2.5471	0.35	0.5057
Discharge (m^3/s)	52.5490		71.9430		24.3960

ASFM Data Record	Version: 1.1.1		1 Bays	9 Paths		
Experiment Title:	d:\ASFM Project Data\Alvkarleby Spillway\Reprocessed Data\Spillway Test 19.xlv					
Location:						
Comment:						
Sample Length :	90 (seconds)					
	Bay A (Spillway)					
	Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
	8/18/99 18:59	3.19	11.01	0.521	2.427	0.602
	8/18/99 18:58	2.835	11.01	0.505	357.975	0.491
	8/18/99 18:56	2.48	11.01	0.492	353.287	0.403
	8/18/99 18:52	2.125	11.01	0.463	359.726	0.649
	8/18/99 18:51	1.77	11.01	0.516	356.771	0.853
	8/18/99 18:49	1.415	11.01	0.608	33.401	0.958
	8/18/99 18:44	1.06	11.01	0.654	42.047	0.765
	8/18/99 18:43	0.705	11.01	0.68	46.217	0.786
	8/18/99 18:41	0.35	11.01	0.586	20.602	0.983
	Bay A Q (m**3/sec)	23.583				
Total Q (m**3/sec):	23.583					
Integration Method:	Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)					
zroof:	4.24 (m)					
zfloor:	0 (m)					

Figure 4-2: Parallel path data for first 0.5m gate opening test.

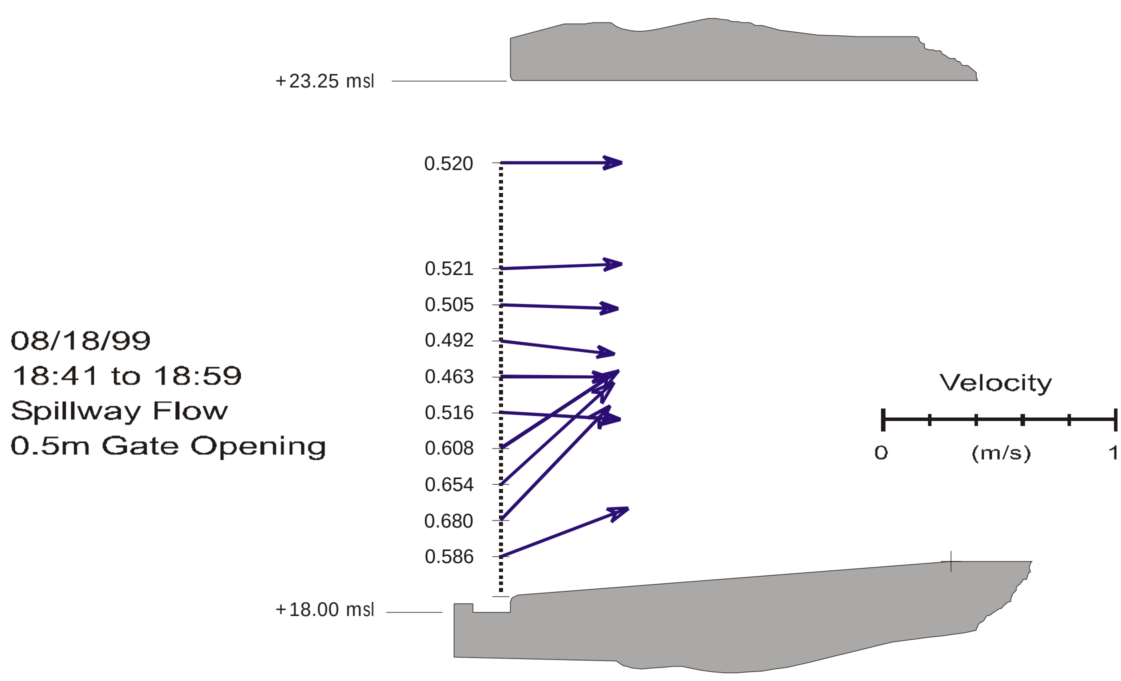

Figure 4-3: Parallel path velocity vector plot for first 0.5m gate opening test.

ASFM Data Record	Version: 1.1.1 Ser. No. 1003		1 Bays	9 Paths		
Experiment Title:	Spillway Test 20					
Location:	Alvkarleby					
Comment:	Gate Opening .5m	Parallel Paths				
Sample Length :	90	(seconds)				
	Bay A (Spillway)					
	Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
	8/18/99 19:09	3.19	11.01	0.401	355.479	0.553
	8/18/99 19:07	2.835	11.01	0.503	342.705	0.512
	8/18/99 19:05	2.48	11.01	0.547	356.088	0.737
	8/18/99 19:15	2.125	11.01	0.424	346.317	0.638
	8/18/99 19:14	1.77	11.01	0.555	29.117	0.912
	8/18/99 19:12	1.415	11.01	0.557	30.196	0.951
	8/18/99 19:22	1.06	11.01	0.652	32.272	0.777
	8/18/99 19:20	0.705	11.01	0.69	45.446	0.795
	8/18/99 19:19	0.35	11.01	0.558	16.458	0.906
	Bay A Q (m**3/sec)	19.369				
Total Q (m**3/sec):	19.369					
Integration Method:	Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)					
zroof:	3.75	(m)				
zfloor:	0	(m)				

Figure 4-4: Parallel path data for second 0.5m gate opening test.

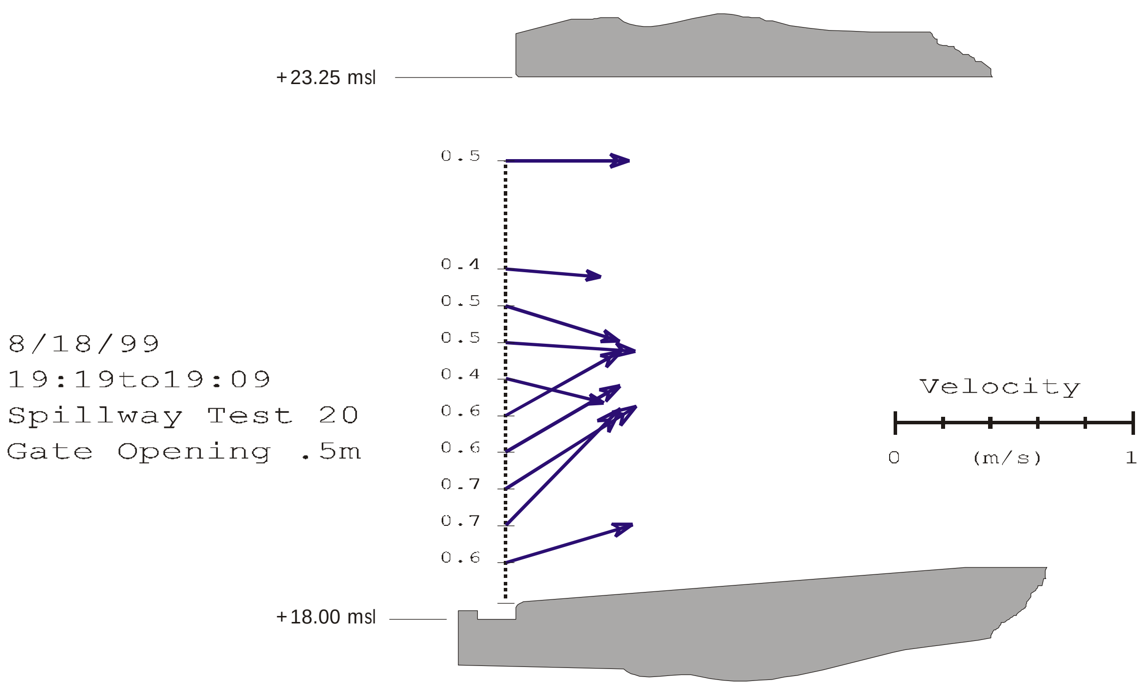

Figure 4-5: Parallel path velocity vector plot for second 0.5m gate opening test.

ASFM Data Record	Version: 1.1.1 Ser. No. 1003	1 Bays	9 Paths		
Experiment Title:	Spillway Test 23				
Location:	Alvkarleby				
Comment:	Gate Opening 0.75 m	Parallel Paths			
Sample Length :	120	(seconds)			

Bay A (Spillway)

Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
8/18/99 21:45	3.19	11.01	0.63	346.595	0.56
8/18/99 21:43	2.835	11.01	0.622	351.67	0.552
8/18/99 21:41	2.48	11.01	0.543	341.963	0.44
8/18/99 21:35	2.125	11.01	0.591	341.193	0.583
8/18/99 21:32	1.77	11.01	0.706	22.224	0.758
8/18/99 21:30	1.415	11.01	0.822	32.841	0.933
8/18/99 21:15	1.06	11.01	0.98	33.654	0.847
8/18/99 21:13	0.705	11.01	1.111	36.696	0.895
8/18/99 21:11	0.35	11.01	1.009	24.638	0.851

Bay A Q (m**3/sec) 38.257

Total Q (m**3/sec): 38.257

Integration Method: Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)

zroof: 4.25 (m)
zfloor: 0 (m)

Figure 4-6: Parallel path data for 0.75m gate opening test.

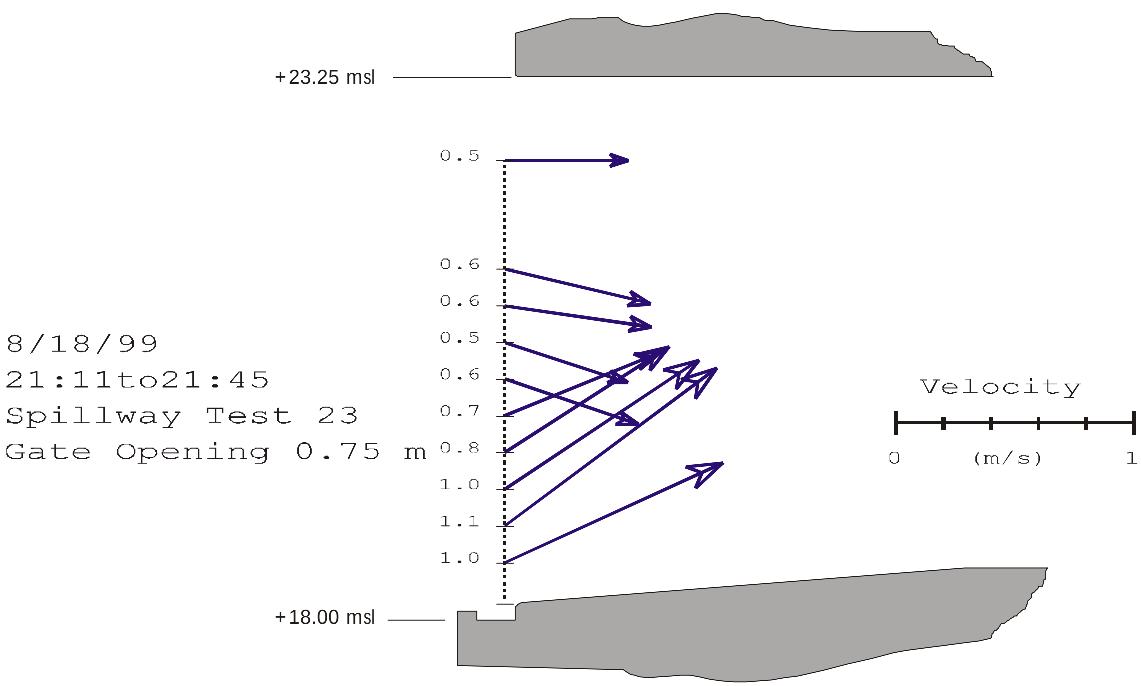

Figure 4-7: Parallel path velocity vector plot for 0.75m gate opening test.

ASFM Data Record	Version: 1.1.1 Ser. No. 1003		1 Bays	9 Paths
Experiment Title:	Spillway Test 21			
Location:	Alvkarleby			
Comment:	Gate Opening 1 m	Parallel Paths		
Sample Length :	120	(seconds)		

Bay A (Spillway)

Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
8/18/99 20:05	3.19	11.01	0.73	347.437	0.605
8/18/99 20:03	2.835	11.01	0.748	352.463	0.686
8/18/99 20:01	2.48	11.01	0.7	343.703	0.595
8/18/99 19:57	2.125	11.01	0.723	350.666	0.572
8/18/99 19:55	1.77	11.01	0.887	30.683	0.85
8/18/99 19:53	1.415	11.01	1.08	27.106	0.813
8/18/99 19:48	1.06	11.01	1.217	38.644	0.9
8/18/99 19:46	0.705	11.01	1.393	43.165	0.875
8/18/99 19:44	0.35	11.01	1.191	20.35	0.886

Bay A Q (m**3/sec) 44.34

Total Q (m**3/sec): 44.34

Integration Method: Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)

zroof: 4.24 (m)
zfloor: 0 (m)

Figure 4-8: Parallel path data for first 1.0m gate opening test.

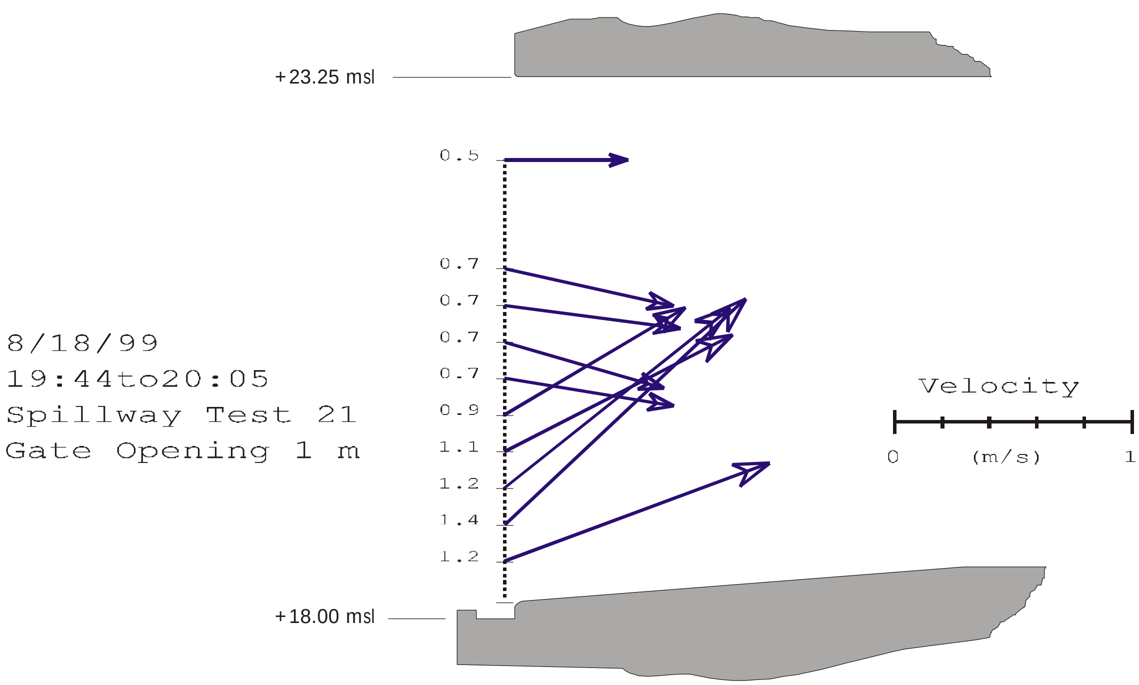

Figure 4-9: Parallel path velocity vector plot for first 1.0m gate opening test.

ASFM Data Record: Version: 1.1.1 Ser. No. 1003 — 1 Bays — 9 Paths
Experiment Title: Spillway Test 22
Location: Alvkarleby
Comment: Gate Opening 1 m — Parallel Paths
Sample Length : 120 (seconds)

Bay A (Spillway)

Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
8/18/99 20:30	3.19	11.01	0.867	3.852	0.539
8/18/99 20:28	2.835	11.01	0.738	351.685	0.571
8/18/99 20:26	2.48	11.01	0.607	353.101	0.581
8/18/99 20:41	2.125	11.01	0.726	12.705	0.375
8/18/99 20:39	1.77	11.01	0.864	21.386	0.82
8/18/99 20:36	1.415	11.01	1.052	25.602	0.916
8/18/99 20:50	1.06	11.01	1.237	39.029	0.897
8/18/99 20:48	0.705	11.01	1.352	43.726	0.881
8/18/99 20:46	0.35	11.01	1.216	21.429	0.905

Bay A Q (m**3/sec) 45.645

Total Q (m**3/sec): 45.645

Integration Method: Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)

zroof: 4.25 (m)
zfloor: 0 (m)

Figure 4-10: Parallel path data for second 1.0m gate opening test.

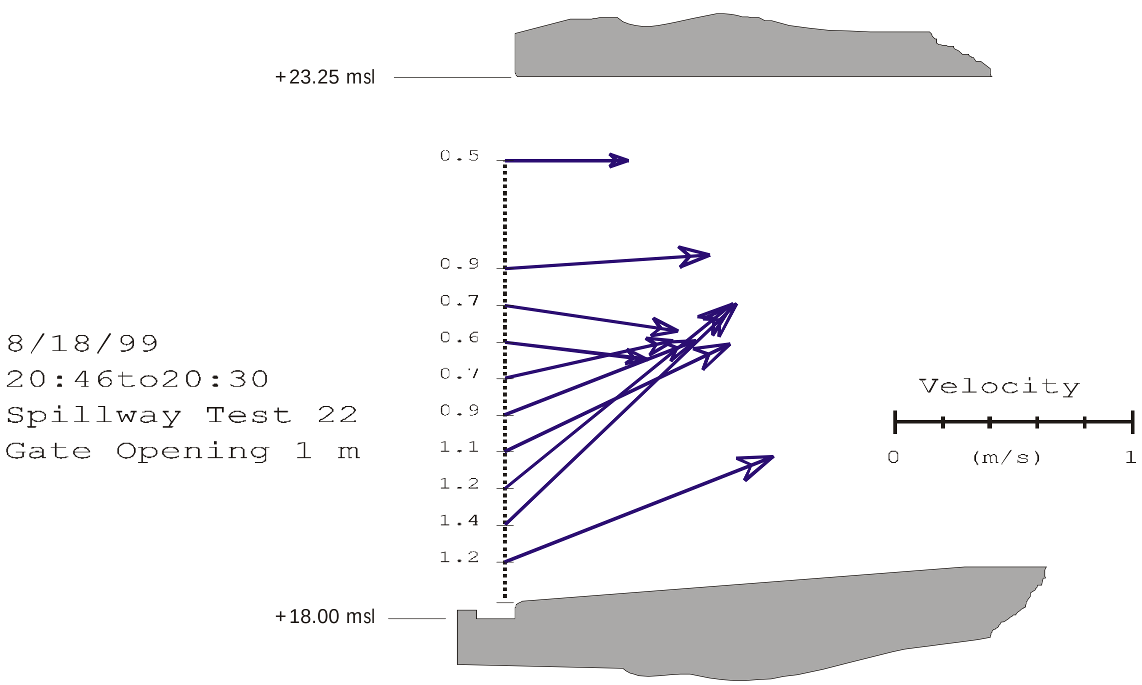

Figure 4-11: Parallel path velocity vector plot for second 1.0m gate opening test.

ASFM Data Record	Version: 1.1.1		1 Bays	10 Paths		
Experiment Title:	Spillway Test 26					
Location:	Alvkarleby					
Comment:	Gate Opening 0.5 m	Converging Paths				
Sample Length :	120	(seconds)				

Bay A (Spillway)

Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
8/18/99 10:45	3.19	11.01	0.577	0.134	1
8/18/99 10:47	2.835	11.01	0.355	3.34	1
8/18/99 10:49	2.48	11.01	0.6	39.717	1
8/18/99 10:45	2.125	11.01	0.553	359.48	1
8/18/99 10:47	1.77	11.01	0.383	4.743	1
8/18/99 10:49	1.415	11.01	0.777	38.9	1
8/18/99 10:45	1.06	11.01	0.575	0.197	1
8/18/99 10:47	0.705	11.01	0.577	27.419	1
8/18/99 10:49	0.35	11.01	0.55	23.155	1

Bay A Q (m**3/sec) 24.396

Total Q (m**3/sec): 24.396

Integration Method: Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)

zroof: 4.24 (m)
zfloor: 0 (m)

__Figure 4-12: Converging path data for 0.5m gate opening test.__

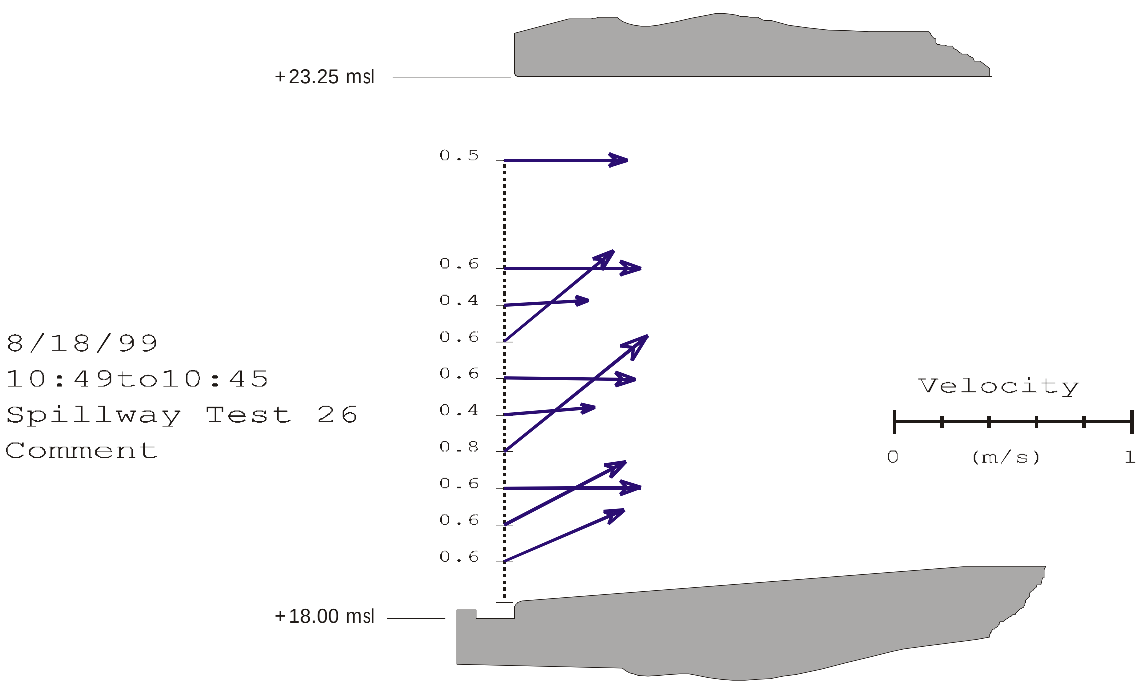

__Figure 4-13: Converging path velocity vector plot for 0.5m gate opening test.__

ASFM Data Record Version: 1.1.1 1 Bays 10 Paths
Experiment Title: Spillway Test 24
Location: Alvkarleby
Comment: Gate Opening 1.0 m Converging Paths
Sample Length : 120 (seconds)

Bay A (Spillway)

Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
8/18/99 10:45	3.19	11.01	1.633	3.729	1
8/18/99 10:47	2.835	11.01	0.591	6.373	1
8/18/99 10:49	2.48	11.01	1.219	37.446	1
8/18/99 10:45	2.125	11.01	0.647	357.348	1
8/18/99 10:47	1.77	11.01	0.555	15.693	1
8/18/99 10:49	1.415	11.01	1.332	42.634	1
8/18/99 10:45	1.06	11.01	1.989	356.008	1
8/18/99 10:47	0.705	11.01	0.857	26.073	1
8/18/99 10:49	0.35	11.01	1.046	19.844	1

Bay A Q (m**3/sec) 52.549

Total Q (m**3/sec): 52.549

Integration Method: Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)

zroof: 4.24 (m)
zfloor: 0 (m)

Figure 4-14: Converging path data for 1.0m gate opening test.

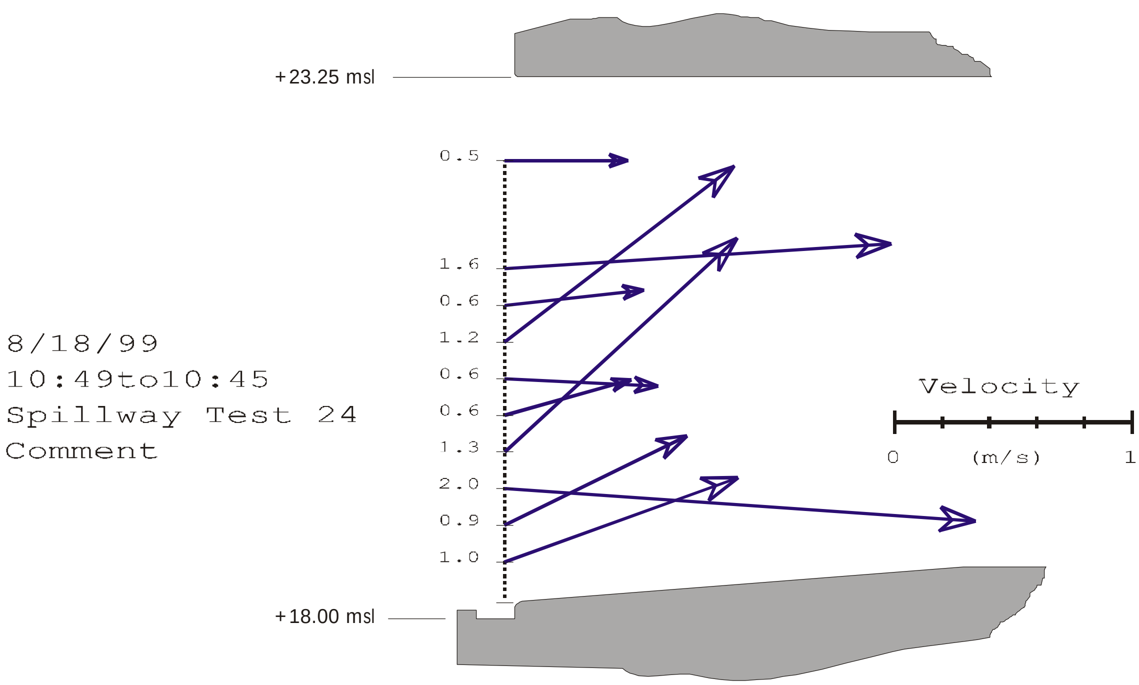

Figure 4-15: Converging path velocity vector plot for 1.0m gate opening test.

ASFM Data Record	Version: 1.1.1		1 Bays	10 Paths
Experiment Title:	Spillway Test 25			
Location:	Alvkarleby			
Comment:	Gate Opening Full	Converging Paths		
Sample Length :	120	(seconds)		

Bay A (Spillway)

Start Date/Time	Z(m)	L(m)	V(m/sec)	Angle(deg)	QI
8/18/99 10:45	3.19	11.01	-99	-99	1
8/18/99 10:47	2.835	11.01	0.979	318.35	1
8/18/99 10:49	2.48	11.01	2.86	42.77	1
8/18/99 10:45	2.125	11.01	1.072	344.43	1
8/18/99 10:47	1.77	11.01	1.25	2.923	1
8/18/99 10:49	1.415	11.01	3.507	47.083	1
8/18/99 10:45	1.06	11.01	0.606	317.912	1
8/18/99 10:47	0.705	11.01	2.234	26.246	1
8/18/99 10:49	0.35	11.01	2.558	5.296	1

Bay A Q (m**3/sec) 71.943

Total Q (m**3/sec): 71.943

Integration Method: Roof: (Open Boundary) ~ Floor: (Closed Boundary, Layer Shape 1/X X=7.0, Entered Thickness=0.100)

zroof: 4.24 (m)
zfloor: 0 (m)

Figure 4-16: Converging path data for fully open gate test.

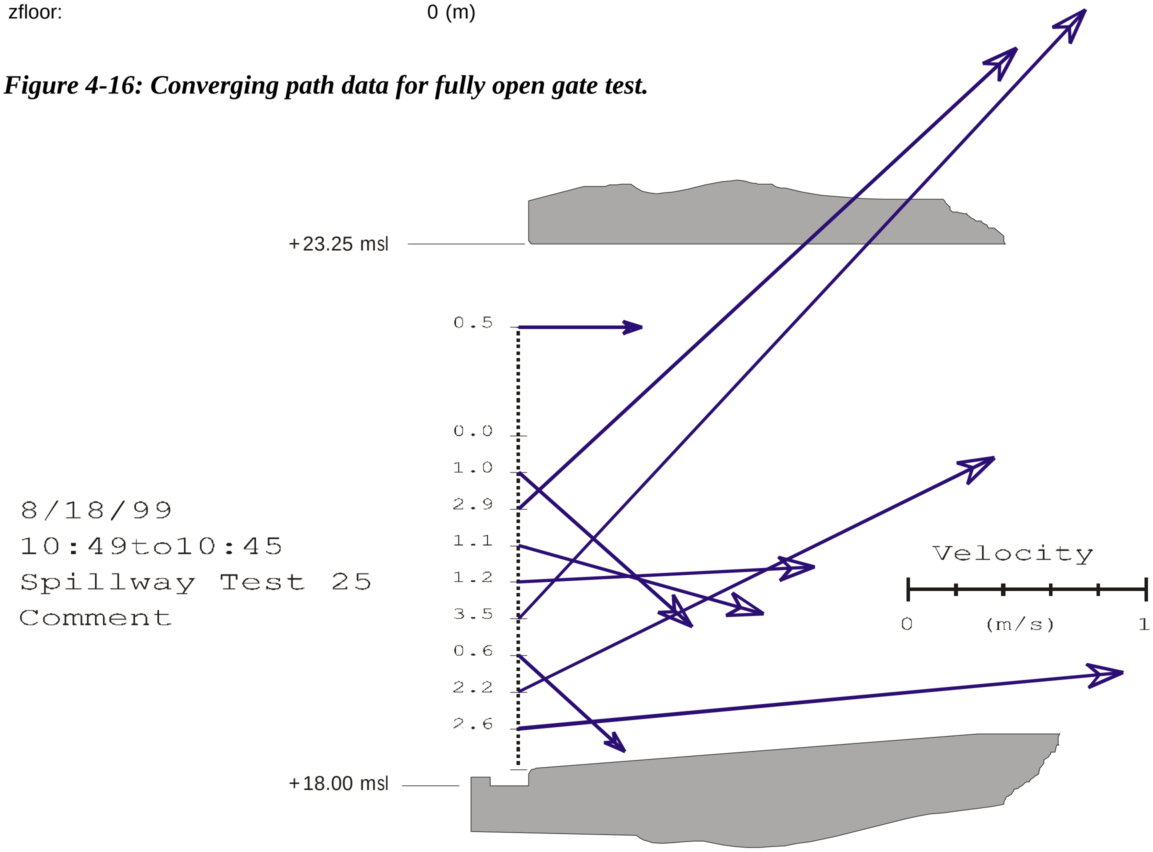

Figure 4-17: Converging path velocity vector plot for fully open gate test.

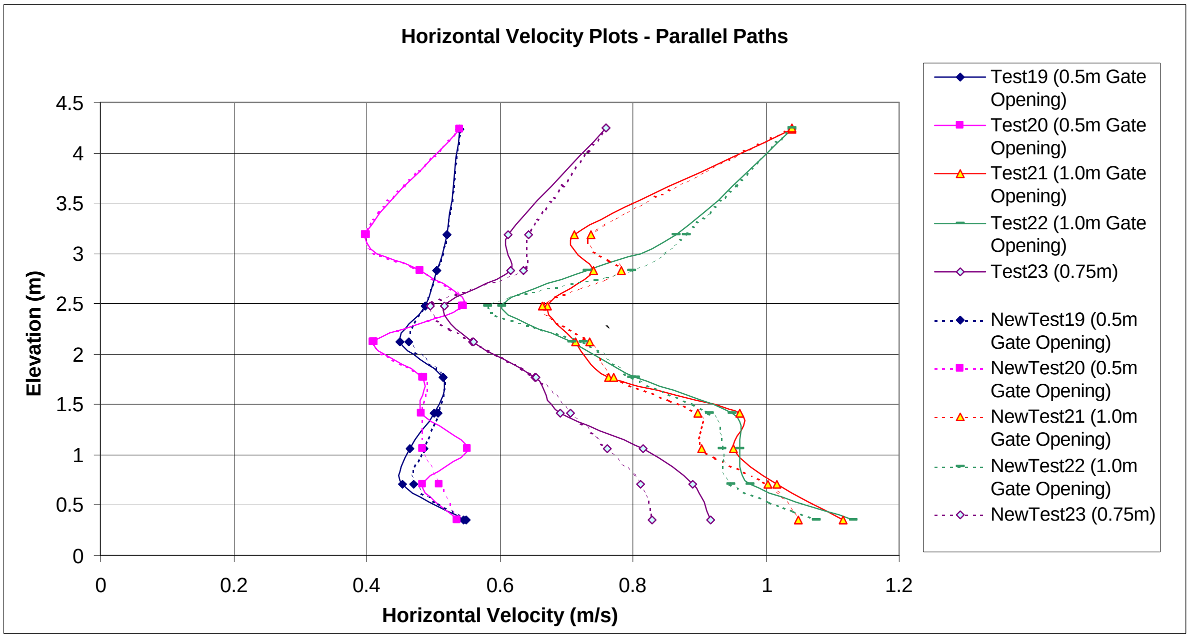

Figure 4-18: Horizontal velocity plots for parallel path data.

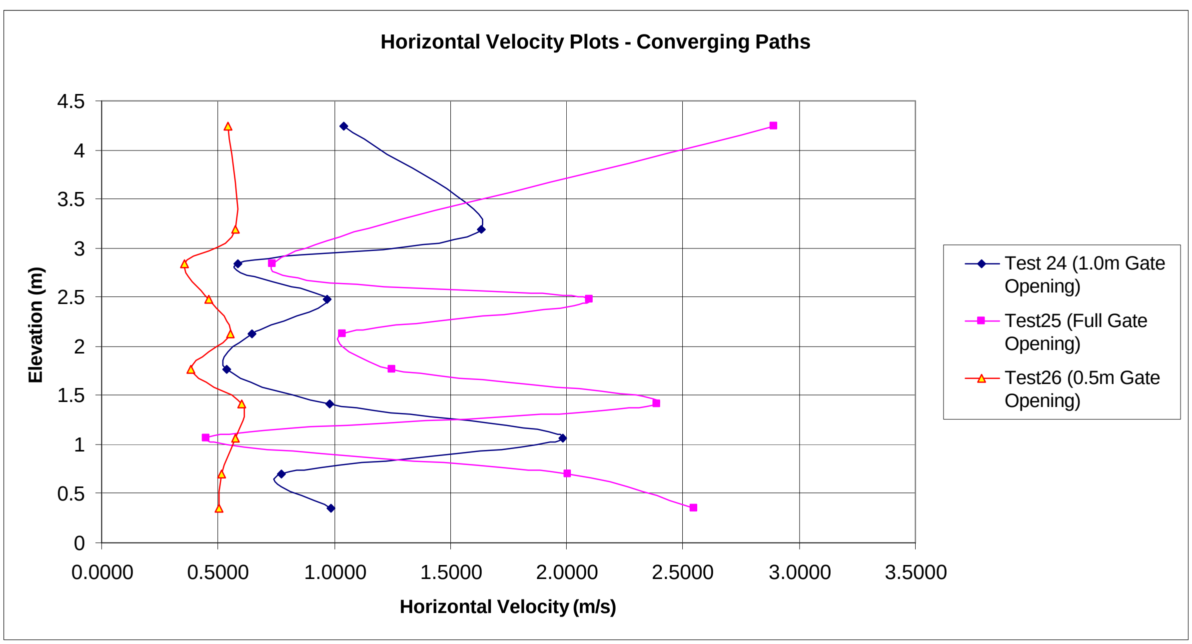

Figure 4-19: Horizontal velocity plots for converging path data.

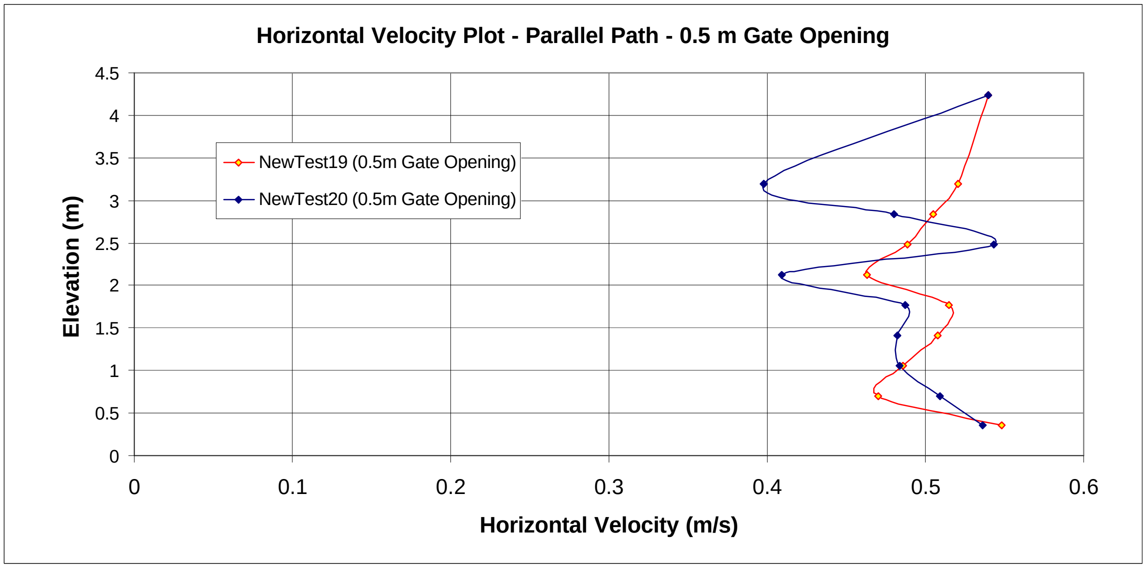

Figure 4-20: Horizontal velocity plot for parallel path data, 0.5m gate opening.

containing the more intense turbulence will bias the velocity estimate since the system is sensitive to a very narrow range of turbulent eddy sizes. Since the region of flow within the boundary layer is experiencing re-circulation and contains more intense turbulence than is in the flow outside of the boundary layer, the velocities would be estimated low resulting in lower discharge estimates.

The ASFM technique shows promise for directly measuring spillway capacity, but the method of mounting the sensors must be improved so that vortex formation and the introduction of air in front of the sensor faces is prevented. Otherwise, as was seen at Alvkarleby, it is not possible to measure the maximum discharge capacity, which is the quantity of interest. Methods to improve the sensor installation are presently being studied, with the intention that a new test can be performed to measure the absolute maximum discharge.

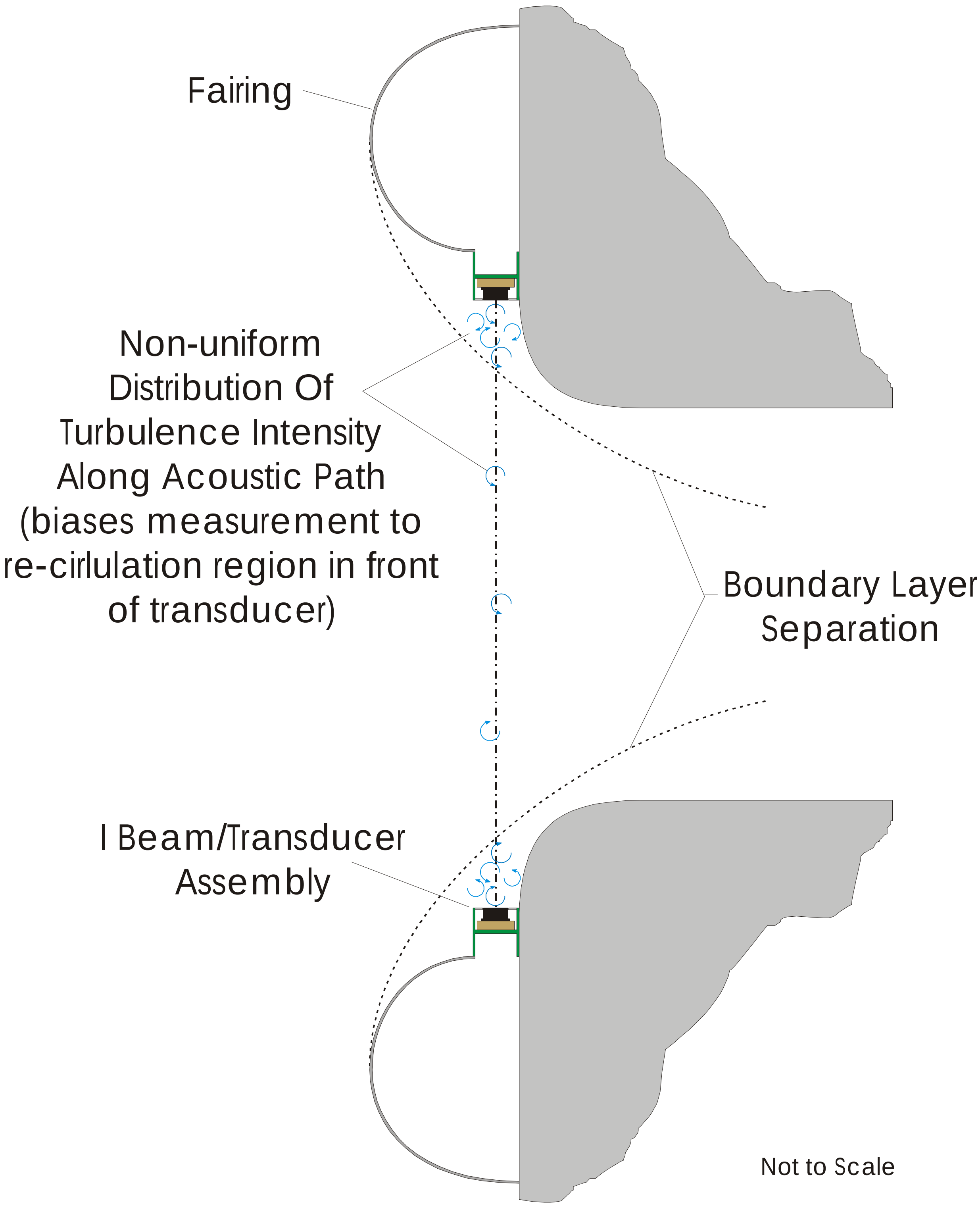

Figure 4-21: Diagram showing boundary layer separation from fairings and resulting non-uniform turbulence distribution along the acoustic path.

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